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RESEARCH MEMORANDUM

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ALTITUDE-TEST-CHAMBER INVESTIGATION OF PERFORMANCE OF A 28-INCH RAM-JET ENGINE

III - COMBUSTION AND OPERATIONAL PERFORMANCE OF THREE FLAME HOLDERS WITH A CENTER PILOT BURNER

By Thomas B. Shillito, George G. Younger
and James G. Henzel, Jr.

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NATIONAL ADVISORY COMMITTEE
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RESEARCH MEMORANDUM

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SUMMARY

A direct-connect altitude-test-chamber investigation of the combustion performance of a 28-inch-diameter ram-jet engine with a can-type center pilot burner has been conducted at the NACA Lewis laboratory. Combustion-chamber configurations employing three different flame holders were investigated at a simulated flight Mach number of 2.0 and altitudes of 45,000, 50,000, and 55,000 feet.

The best of the three configurations investigated had a peak combustion efficiency of about 0.90 and an operating fuel-air ratio range varying from 0.019 to 0.099 at an altitude of 45,000 feet and from 0.021 to 0.053 at an altitude of 50,000 feet. A comparison of the best configuration employing a pilot burner with configurations without a pilot burner, which were previously investigated, showed that the pilot-burner configuration was superior because of its lower lean limits of combustion. The differences in steady-burning performance were small over the comparable range of fuel-air ratios for configurations with and without pilot burners.

INTRODUCTION

An investigation of the altitude performance of a 28-inch-diameter ram-jet engine has been conducted in a 10-foot-diameter altitude chamber at the NACA Lewis laboratory. This engine is being developed by the Marquardt Aircraft Company for use in a Grumman Aircraft Engineering Corporation test vehicle as part of a Navy guided-missile project. The missile is to be launched by a rocket booster and is to climb under its own power to a cruising altitude of 50,000 feet. The vehicle control systems are designed to maintain a Mach number of 2.0 during the climb and cruise conditions.

Results of altitude-test-chamber investigations of this engine for combustion-chamber configurations employing 10 different gutter-type flame holders with the same fuel-injection system are reported in references 1 and 2. The range of flame-holder geometry covered was sufficient to indicate an optimum design of simple gutter-type flame holder to be used for the combustion chamber then being investigated. Because the investigations of references 1 and 2 indicated that a center pilot burner in conjunction with the general type of flame holder being used might lead to performance improvements in the lean range of fuel-air ratios, the investigation reported herein was conducted. 2025

The performance investigation included operation over the stable-burning range of fuel-air ratios for a simulated Mach number of 2.0 at altitudes of 45,000, 50,000, and 55,000 feet. Two annular-gutter flame holders similar to those of reference 2 and one radial-gutter flame holder were used. Rich and lean limits of combustion, combustion efficiencies, and other combustion-chamber variables are presented. A comparison of the combustion performance of configurations with and without a pilot burner is also presented.

APPARATUS

Description of Engine

A schematic diagram of the test engine is shown in figure 1. The inner body contours, including the diffuser cone, and the inside contours of the outer shell aft of station 31 correspond to those of the flight engine. The bellmouth convergent-divergent inlet nozzle surrounding the cone accelerated the inlet air from stagnation conditions in the test chamber to a Mach number of about 1.6 at station 31. Station 31 corresponds to the lip location of the flight engine and 1.6 is the expected lip Mach number of the flight engine at a flight Mach number of 2.0. Four inner-body support longerons spaced 90° apart and extending from station 35 to the aft end of the inner body formed four separate flow channels for the air entering the combustion chamber. The flame holders and the center pilot burner were mounted at the aft end of the inner body. The combustion chamber, most of which was water-jacketed, had an inside diameter of 28 inches and an effective length of approximately 57 inches. The throat area of the convergent-divergent exhaust nozzle following the combustion chamber was 55 percent of the combustion-chamber area.

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Installation in Altitude Chamber

A schematic diagram of the engine mounted in the altitude test chamber is shown in figure 2. A forward baffle attached to the engine by means of a flexible seal isolated the inlet air supply from the low-pressure compartment provided for the engine exhaust. A rear baffle surrounding the engine near the exhaust nozzle prevented recirculation of the hot exhaust gases around the engine. Other details of the installation are given in reference 1.

Pilot Burner

The inner body of the engine used for the investigations of references 1 and 2 tapered to a point at the aft end, where the flame holder was mounted. The inner body was approximately the same length for the pilot-burner configurations as for the configurations of references 1 and 2, but terminated bluntly instead of tapering to a point. A can-type burner was mounted on the blunt end of the inner body at station 238 in the engine.

An exploded view of the pilot burner and the flame holder is shown in figure 3. The pilot burner consisted of a swirl plate, 6 inches in diameter, mounted over 1/2-inch spacers on the blunt end of the inner body and a skirt 4.4 inches long mounted on the swirl plate and flaring to a diameter of 7.8 inches at the downstream end. The swirl plate incorporated radial louvers punched and bent 30° from the surface to form flap-type openings for admission of a swirling primary air supply. The flow of primary air into the pilot burner was from the 1/2-inch space provided between the inner body and the swirl plate. Holes 5/8 inch in diameter punched in the skirt admitted the main air supply for the pilot burner.

Fuel for the pilot burner was admitted through a commercial conical spray nozzle in the center of the swirl plate. The pilot-burner fuel nozzle, spraying aft, was rated at 28 gallons per hour at a pressure differential of 100 pounds per square inch. A spark plug located below the fuel nozzle was used for ignition in the test engine.

Flame Holders

The three flame holders used were constructed of interconnected 60° included-angle V cross section gutters with the apex of the V's pointed in the upstream direction. On each flame holder, four small radial gutters fitted into notches in the pilot-burner skirt to connect the main flame-holding system of gutters to the pilot burner. The flame holders were mounted on the outer shell at station 240. The following summary gives the essential features of the flame holders investigated: 2025

Configuration 1 had a flame holder, shown in figure 4, with four 1.38-inch wide, staggered, annular gutters. These gutters were interconnected by radial plates (parallel to air stream) with gutter segments attached to the downstream side. The projected blocked area was 54.0 percent of the combustion-chamber area.

Configuration 2 had a flame holder, shown in figure 5, with two 2.00-inch wide, staggered, annular gutters interconnected by radial-gutter struts. The projected blocked area was 45.0 percent of the combustion-chamber area.

Configuration 3 had a flame holder, shown in figure 6, with 12 radial gutters 1.15 inches in width at inner radius flaring to 2.00 inches in width at outer radius. The radial gutters were interconnected near each end by 1.00-inch wide annular-gutter struts. The projected blocked area was 41.0 percent of the combustion-chamber area.

An additional blocked area of 7.7 percent resulted from the presence of the pilot burner (based on the 7.8-in. diameter of the near aft end of the skirt).

Flare cases (similar to ones contemplated for use in starting the flight engine) were mounted in three locations on each flame holder (figs. 4, 5, and 6). On each of the flame holders, one of these flare cases had holes punched in the wall for admission of air and was equipped with a fuel nozzle and spark plug, which provided an alternate igniter for the engine when the pilot-burner ignition failed to operate.

Fuel-Injection System

Fuel was injected at station 208 through eight circular-arc manifold segments arranged in pairs in each of the four quadrants (formed by the inner-body support longerons) to form two concentric manifolds. The concentric-circle arrangement, in contrast to the staggered arrangement for references 1 and 2, was in accordance with the flight-engine configuration anticipated at the time the runs reported were made. Each pair of manifold segments was supported by a hollow streamlined strut that passed through the outer shell. Each of these struts also served as the fuel-supply channel for the manifold segments and was divided into two flow passages to permit individual control of flow to either the inner or outer manifold segment. Each of the two manifold rings was supplied by a can-type flow divider, to which the fuel pressure was regulated by a throttle valve. A pressure balancing line between the flow dividers provided for equal fuel pressure to all eight manifold segments when desired.

Each manifold was equipped with spring-loaded fuel-injection nozzles, similar in design to those described in reference 1, which were directed upstream. Twenty-four fuel nozzles were installed in the outer manifold (six in each quadrant) and were inclined at an angle of 1° toward the engine center line. Sixteen fuel nozzles were installed in the inner manifold (four in each quadrant) and were inclined at an angle of 3° toward the engine center line. The outer ring of nozzles was at a radius of 12.4 inches and the inner ring of nozzles was at a radius of 9.0 inches. The radii of the outer shell and inner body in the plane of the fuel-nozzle discharge were 14.0 and 7.3 inches, respectively.

Instrumentation

Fuel flow was measured with a calibrated adjustable orifice meter. Air flow was determined from a calibration of the choked bellmouth inlet nozzle of the engine. This calibration, established during the investigations reported in references 1 and 2, was used instead of direct measurements of air flow obtained from a sharp-edge orifice in the inlet-air supply line in order to reduce data scatter brought about by air-flow-measurement pressure fluctuations.

The locations of temperature, static-pressure, and total-pressure measurements within the engine are shown in figure 1. Engine-inlet total temperature and pressure were measured by thermocouple and pressure rakes at the bellmouth entrance. Total- and static-pressure surveys across the annular diffuser were made approximately 13 inches upstream of the flame holder in two of the four quadrants. Static pressures were measured, for reference purposes, along the wall of the inner body and along the wall of the water-jacketed combustion chamber. Water-cooled rakes were used to measure total pressure at the combustion-chamber outlet. Static pressure in the exhaust-nozzle throat was measured by wall static taps and by water-cooled trailing static tubes (having a length-diameter ratio of 27) mounted on the water-cooled total-pressure rakes in the combustion-chamber outlet. 2025

PROCEDURE

The investigation reported herein was for a simulated free-stream Mach number of 2.0 at altitudes of 45,000, 50,000, and 55,000 feet. The fuel-air ratio range covered was from lean blow-out to rich blow-out or, if rich blow-out did not occur, to some fuel-air ratio above 0.07.

The inlet air was preheated to 250° F to simulate the ram temperature at a flight Mach number of 2.0 in the altitude range investigated by mixing the products of combustion from an air heater with the inlet-air supply. An air-heater fuel-air ratio of about 0.002 was required to maintain an inlet-air temperature of 250° F. With the heater in operation, the pilot burner or flare-case igniter was ignited at a bellmouth-inlet total pressure of about 40 inches of mercury absolute and an engine-outlet static pressure of about 25 inches of mercury absolute. These conditions resulted in a burner-inlet velocity of about 200 feet per second for the starts. After the main fuel flow was started and burning in the combustion chamber was established, the exhaust pressure was reduced to a value below that required to choke the exhaust nozzle; the exhaust nozzle remained choked for all runs.

In order to simulate a given altitude for the steady-burning runs, the stagnation pressure at the bellmouth inlet was set to a value corresponding to that behind the oblique shock off the diffuser cone of the flight engine. The air flow for the test engine, as determined by the bellmouth-inlet pressure setting, corresponded to that for supercritical operation of the flight engine; there were no provisions on the test engine for subcritical air-flow spillover simulation. With the inlet pressure and temperature set, the fuel-air ratio was varied in small increments and data were taken at stabilized burning conditions.

The runs were made with a constant pilot-burner fuel pressure, which was established by investigating its effect on lean limit of combustion for configuration 1 at simulated altitudes of 45,000 and

55,000 feet. The leanest limits of combustion occurred at a pilot-burner fuel pressure of 150 pounds per square inch for both altitudes. This pressure was used for all burning runs for the three configurations investigated. A check at a simulated altitude of 55,000 feet and a fuel-air ratio of 0.035 showed that changing the pilot fuel pressure from 50 to 150 pounds per square inch did not affect the combustion efficiency.

The contribution of the pilot burner to the total fuel flow supplied to the combustion chamber varied from 2 percent at the highest rates of total fuel flow investigated to 11 percent at the lowest rates.

In order to conform with the objectives of the preliminary phases of the missile development program for this engine, the fuel used in this investigation, as well as that of references 1 and 2, was commercial-grade normal heptane. Two methods of fuel injection were used and are defined as follows:

1. Uniform injection: Injection at equal fuel pressures through all nozzles in both inner and outer manifolds.

2. Annular injection: Injection through nozzles in inner manifold only.

Annular injection was used to extend the operating range to leaner fuel-air ratios than were generally possible with uniform injection.

Blow-out was detected by the change in sound level, observation of blow-out through a periscope viewing the discharge of the engine, and automatic fuel-flow cut-off through the action of a photoelectric flame-sensing element attached to the combustion chamber. The fuel flow and the bellmouth-inlet total pressure observed at the time of blow-out were used to determine the fuel-air ratio defining the limits of combustion.

The symbols and the station locations used throughout the report are defined in the appendix. Combustion efficiencies were calculated by the methods outlined in reference 2.

RESULTS AND DISCUSSION

Configuration 1

The combustion-chamber performance variables at simulated altitudes of 45,000, 50,000, and 55,000 feet for configuration 1 are presented in figure 7. As illustrated in references 1 and 2, the

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gas-flow factor p_5A_5/w_5 is approximately proportional to the square root of the combustion-chamber-outlet temperature. The data in figure 7(a) show that for annular injection the combustion-chamber-outlet temperature increased as the fuel-air ratio increased from 0.02 to 0.04 and that for uniform injection a similar trend 2025 occurred with increasing fuel-air ratio up to a value of approximately 0.06, above which there was a slight decrease. For both annular and uniform injection, the combustion-chamber-outlet temperature at a given fuel-air ratio decreased with increasing altitude.

Combustion efficiencies computed from the data in figure 7(a) are presented in figure 7(b) as functions of fuel-air ratio and simulated altitude. At a constant simulated altitude, the pressure and the velocity at which combustion occurred varied with fuel-air ratio according to the requirements for continuity of mass flow through the choked exhaust nozzle. The variations in combustion efficiency shown in figure 7(b) were therefore functions of the combined effects of three variables: fuel-air ratio, pressure, and velocity. The simultaneous variations of these three variables are represented by plots of combustion-chamber-outlet total pressure and combustion-chamber-inlet Mach number as functions of fuel-air ratio; these plots are shown in figures 7(c) and 7(d), respectively.

The combustion efficiency was almost constant at a value of 0.9 between fuel-air ratios of 0.06 and 0.09 for simulated altitudes of 45,000 and 50,000 feet. At constant simulated altitude, combustion efficiencies obtained with uniform injection decreased very rapidly as the fuel-air ratio was reduced below approximately 0.050. These reductions in combustion efficiency with decreasing fuel-air ratio were accompanied by pronounced decreases in combustion-chamber-outlet pressure and increases in combustion-chamber-inlet Mach number.

Within the comparable range of fuel-air ratios for which data were obtained, annular injection resulted in higher combustion efficiencies than were obtained with uniform injection. At a fuel-air ratio of 0.04, the combustion efficiency for annular injection was 0.14 higher than for uniform injection at 45,000 feet and 0.08 higher at 55,000 feet. Although no data were obtained for fuel-air ratios greater than 0.041 for annular injection, the trends of the curves in figures 7(a), 7(b), and 7(c) indicate that a superiority in combustion efficiency for annular injection would be maintained up to a fuel-air ratio of about 0.047.

Steady-burning points were obtained over a range of combustion-chamber-outlet pressures from 670 to 2000 pounds per square foot, as shown in figure 7(c), where the limits of combustion are also presented. The lean limit of combustion for annular injection increased from a fuel-air ratio of 0.019 to 0.021 as the simulated altitude increased from 45,000 to 55,000 feet and for uniform injection increased from 0.031 to 0.033 for the same increase in altitude. The rich limit of combustion decreased from a fuel-air ratio of 0.099 (not shown on fig. 7(c)) at a simulated altitude of 45,000 feet to 0.053 at 55,000 feet, resulting in a rapidly narrowing operating range as the altitude increased. Similarity of slopes of the curves defining the rich limit of combustion and steady burning in a region of fuel-air ratio common to both indicates that at an altitude of 55,000 feet the resulting pressure levels in the combustion chamber were almost the minimum values at which stable combustion could be maintained at all fuel-air ratios.

The method used to determine combustion-chamber-inlet Mach number from total- and static-pressure measurements ahead of the flame holder is explained in reference 1. Values of Mach number obtained in the two quadrants did not agree at similar conditions of operation and the data presented in figure 7(d) were selected from the quadrant that gave values most consistent with theoretical values determined from the fuel-air ratio and combustion efficiency.

The ratio of combustion-chamber-outlet to -inlet total pressure (fig. 7(e)) was almost a constant value of 0.925 between fuel-air ratios of 0.04 and 0.07 and decreased to a value of about 0.88 at a fuel-air ratio of 0.02. Simulated altitude or pressure level in the combustion chamber had a slight effect on the pressure ratio. The combustion-chamber pressure losses are of interest only at fuel-air ratios for critical or subcritical operation of the ram-jet engine. When the ram-jet engine is operating supercritically, the mass flow into the inlet is fixed by the free-stream Mach number and altitude. Thus the combustion-chamber-outlet pressure, and therefore the combined pressure losses in the combustion chamber and the diffuser, are fixed by the combustion temperature and the fuel flow.

The ratio of the combustion-chamber-outlet total pressure to exit-nozzle-throat static pressure shown in figure 7(f) was a function of the type of injection and, for uniform injection, increased with increasing fuel-air ratio. From considerations of isentropic flow between stations 4 and 5, ideal one-dimensional choked flow at station 5, and the physical properties of the gas, the pressure ratio would be expected to decrease from 1.87 in the low range of fuel-air ratios to 1.81 in the high range. Because combustion efficiency is based on a combustion temperature obtained from mass flow and pressure measurements (reference 2), these unusual variations in exhaust-nozzle pressure ratio obtained in the investigation indicate a possible departure from ideal one-dimensional flow and, consequently, slight errors in obtained values of combustion efficiency. 2025

Burning for this configuration was generally smooth, and blowout occurred suddenly and without warning. Near the lean limit of combustion, visible flame was confined to the center of the burner for both annular and uniform fuel injection.

Configuration 2

The performance variables for configuration 2 are presented in figure 8. The peak combustion efficiencies obtained with uniform injection (fig. 8(b)) were slightly lower, and the decrease in combustion efficiency with decreasing fuel-air ratio was not as pronounced as for configuration 1. Combustion efficiencies obtained with annular injection were about equal to those for configuration 1 at similar altitudes.

The lean limit of combustion with annular injection (fig. 8(c)) varied from a fuel-air ratio of 0.025 at a simulated altitude of 45,000 feet to 0.029 at 55,000 feet. The rich limit of combustion with uniform injection, obtained only at a simulated altitude of 55,000 feet, was at a fuel-air ratio of 0.069. Operation at simulated altitudes of 45,000 and 50,000 feet was obtained at fuel-air ratios greater than 0.07.

Insofar as practical operation is concerned, both configurations 1 and 2 have similar maximum useable fuel-air ratios of 0.065 or 0.070 at and below altitudes of 50,000 feet. Operation at higher fuel-air ratios approaching the rich limit of combustion for either configuration would yield no significant thrust increases for the increases in fuel consumption. On the basis of lean limits of combustion, however, configuration 2 is inferior to configuration 1.

Over the entire fuel-air ratio range for configuration 2 the combustion-chamber pressure ratio (fig. 8(e)) was approximately equal to that obtained for configuration 1. Burning characteristics for this configuration were also similar to those for configuration 1.

Configuration 3

The combustion-chamber performance variables for configuration 3 are shown in figure 9. Below fuel-air ratios of 0.055, the combustion efficiencies obtained with uniform injection (fig. 9(b))
2025 were higher than those for configurations 1 and 2. Above fuel-air ratios of 0.055, the combustion efficiencies were about equal to those obtained for configurations 1 and 2.

The use of annular injection resulted in essentially no improvement in the lean limit of combustion. Blow-outs with annular injection were encountered at fuel-air ratios of 0.032, 0.036, and 0.039 for a simulated altitude of 45,000 feet and, as can be seen in figure 9(c), these limits almost bracketed the annular injection steady-burning points. This lack of improvement in the lean limit of combustion indicates that local enrichment alone is insufficient for realization of combustion-limit improvement; the zones of fuel-air-ratio enrichment must coincide to the fullest extent possible with the areas of blockage provided by the flame holder. Because the flame holder for configuration 3 was predominantly a radial-gutter type, the use of local enrichment in quadrants (as in reference 1) might have resulted in improvement in the lean limit of combustion.

The combustion-chamber pressure ratio (fig. 9(e)) was from 2 to 3 percent higher than for configurations 1 and 2. Burning characteristics, other than slightly rough and erratic operation at lean fuel-air ratios, were similar to those for configurations 1 and 2.

Configuration 3 was the poorest of the three configurations investigated, primarily because of failure of annular injection to extend the lean limit of combustion.

Comparison of Configurations with and without Pilot Burner

The configurations of references 1 and 2 had a subsonic diffuser afterbody that tapered to a point at the aft end and incorporated two longitudinally staggered circular fuel manifolds. These features contrast with the blunt-end afterbody and concentric-circle fuel manifold arrangement of the pilot-burner configurations. The differences in performance of configurations with and without pilot burners must therefore be attributed to the combined effects of all the differences in physical configuration and not only to the action of the pilot burner. The blocked areas of the flame holders for configurations with the pilot burner and the configurations of reference 2 are within a comparable range.

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A comparison of the limits of combustion for pilot-burner configuration 1 of this report with two of the best configurations of reference 2 is shown in figure 10. Flame holders 3 and 5 of reference 2 were used in these configurations. Both flame holders had 2.00-inch annular gutters, and the percentage blocked areas were 45.0 and 60.0, respectively. At a simulated altitude of 50,000 feet, the rich-limit fuel-air ratio with uniform injection was essentially the same (about 0.077) for all three configurations. The behavior of the rich limits with altitude were different, however, with the pilot-burner rich limit being more sensitive to changes in altitude. The lean-limit fuel-air ratios with annular injection increased with altitude at approximately the same rate for all three configurations. The lean-limit fuel-air ratio was about 0.02 for the pilot-burner configuration, compared with approximately 0.03 for the two configurations without a pilot burner. This lean-limit superiority of the pilot-burner configuration is particularly significant because the two configurations from reference 2 were among those with the leanest combustion limits.

A comparison of combustion efficiencies and combustion-chamber pressure ratios at a simulated altitude of 45,000 feet for configurations with and without pilot burners is shown in figure 11. Over the entire range of fuel-air ratios covered, the differences between obtainable combustion efficiencies for the pilot-burner configuration and the configurations without pilot burners was small. Above a fuel-air ratio of 0.05, the combustion efficiency for the pilot-burner configuration was consistently lower than for the flame holder 5 configuration of reference 2.

The combustion-chamber pressure ratios (fig. 11(b)) were almost equal (0.92) for both the pilot-burner configuration and flame holder 5 of reference 2. The pilot-burner configuration had a combustion-chamber pressure ratio about 2 percent lower than that for the flame holder 3 configuration of reference 2.

A plot of the ratio of combustion-chamber-outlet stagnation pressure to altitude ambient pressure as a function of fuel flow is presented in figure 12 for the three configurations at a simulated altitude of 45,000 feet. This over-all pressure ratio is a relative measure of thrust and these curves permit a properly evaluated comparison of configurations because the combined effects of combustion efficiency and combustion-chamber pressure ratio are included. On the curves for annular injection, points are shown to indicate the lean limits of combustion. The subsonic-diffuser critical points shown on the curves for uniform injection were 2025 estimated on the basis of a normal shock at the cone-surface Mach number of the flight engine, a total-pressure ratio of 0.93 in the subsonic diffuser, and the combustion-chamber pressure ratios shown in figure 11(b). The portion of the curves extending to pressure ratios greater than the diffuser critical values in figure 12 are meaningless because of the direct-connect features of the test installation, but were retained primarily for curve identification.

The pilot-burner configuration and the flame holder 5 configuration of reference 2 had the same over-all pressure ratios, and hence thrust, at the critical point but the fuel flow for the pilot-burner configuration was 7.5 percent greater. The pilot-burner configuration had an over-all pressure ratio at the critical point 2.5 percent lower than that for the flame holder 3 configuration.

The pilot-burner configuration would permit operation at a minimum over-all pressure ratio of 3.3 compared with approximately 4.1 for the configurations without pilot burners. Thus, the pilot-burner configuration had approximately the same performance over the comparable operating range of fuel-air ratios but enabled operation at lower values of fuel flow and thrust before lean blow-out was encountered. A greater combustion-chamber performance range would therefore be available for adaption to the requirements of the desired missle flight plan.

SUMMARY OF RESULTS

A direct-connect altitude-test-chamber investigation of the combustion performance of a 28-inch ram-jet engine with a can-type center pilot burner has been conducted at a simulated free-stream Mach number of 2.0 and altitudes of 45,000, 50,000, and 55,000 feet. Configurations employing two different annular-gutter flame holders and one radial-gutter flame holder were investigated. The following results were obtained:

1. The configuration employing a four-ring annular-gutter flame holder was the best of the three configurations investigated, primarily because of better lean limits of combustion.

2. The configuration employing the four-ring annular-gutter flame holder blocking 54.0 percent of the combustion-chamber area had an operating fuel-air-ratio range varying from 0.019 to 0.099 at 45,000 feet and from 0.021 to 0.053 at 55,000 feet. The rich limits of combustion were obtained with uniform fuel injection (equal fuel pressures to both of the concentric-ring manifolds) and the lean limits with annular injection (injection with the inner manifold only). 2025

3. A comparison of lean burning limits for the three configurations investigated indicated that improvement of the lean limits of combustion by local fuel-air ratio enrichment can be accomplished only through provision of flame-holder blockage to coincide with the zones of fuel-air enrichment.

4. A constant combustion efficiency of about 0.9 was obtained with the four-ring annular-gutter flame holder between fuel-air ratios of 0.06 and 0.09. Combustion efficiencies obtained with uniform injection decreased rapidly as the fuel-air ratio was reduced below 0.050; combustion efficiencies with annular injection were higher than for uniform injection within the comparable range of fuel-air ratios (0.04 and below).

5. Comparison of performance of the pilot-burner configuration employing the four-ring annular-gutter flame holder with configurations without a pilot burner showed that performance differences within the comparable range of steady-burning fuel-air ratios were small. The pilot-burner configuration was best, however, because its lean limit of combustion was at a fuel-air ratio of approximately 0.02 compared with approximately 0.03 for the configurations without the pilot burner.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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APPENDIX - SYMBOLS

The following symbols are used throughout this report:

A	area, sq ft
M	Mach number
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
w	weight flow, lb/sec
η	combustion efficiency

Subscripts:

a	altitude ambient
0	conditions at test-engine inlet (station 0)
2	conditions at combustion-chamber inlet (station 228)
2'	conditions at station 2 adjusted to combustion-chamber area
4	conditions at combustion-chamber outlet (station 292)
5	conditions at exhaust-nozzle throat (station 309)

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1. Jones, W. L., Shillito, T. B., and Henzel, J. G., Jr.: Altitude-Test-Chamber Investigation of Performance of a 28-Inch Ram-Jet Engine. I - Combustion and Operational Performance of Four Combustion-Chamber Configurations. NACA RM E50F16, 1950.

2. Shillito, T. B., Jones, W. L., and Kahn, R. W.: Altitude-Test-Chamber Investigation of Performance of a 28-Inch Ram-Jet Engine. II - Effects of Gutter Width and Blocked Area on Operating Range and Combustion Efficiency. NACA RM E50H21, 1950.

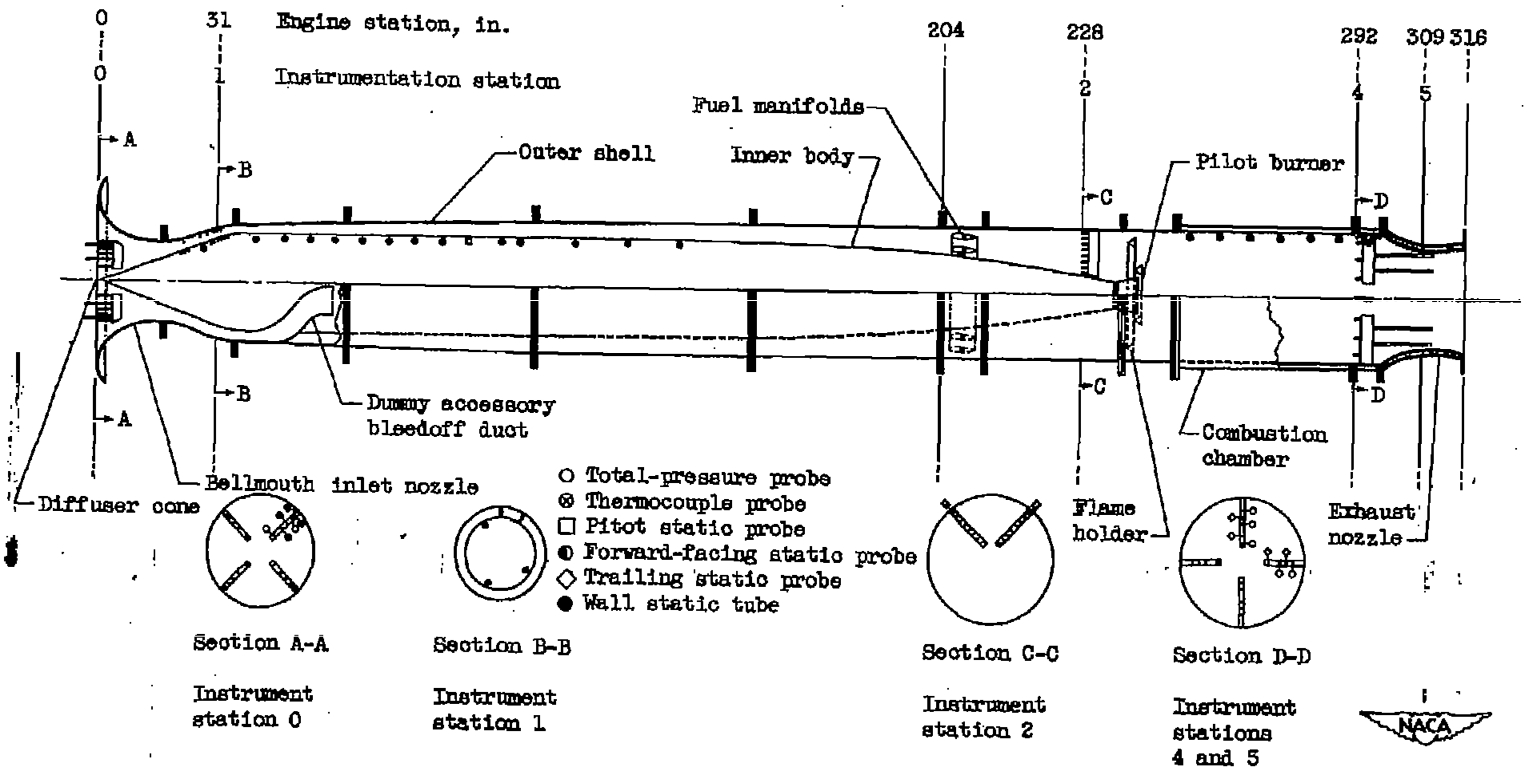

Figure 1. - Schematic diagram of 28-inch ram-jet engine showing instrumentation and station locations.

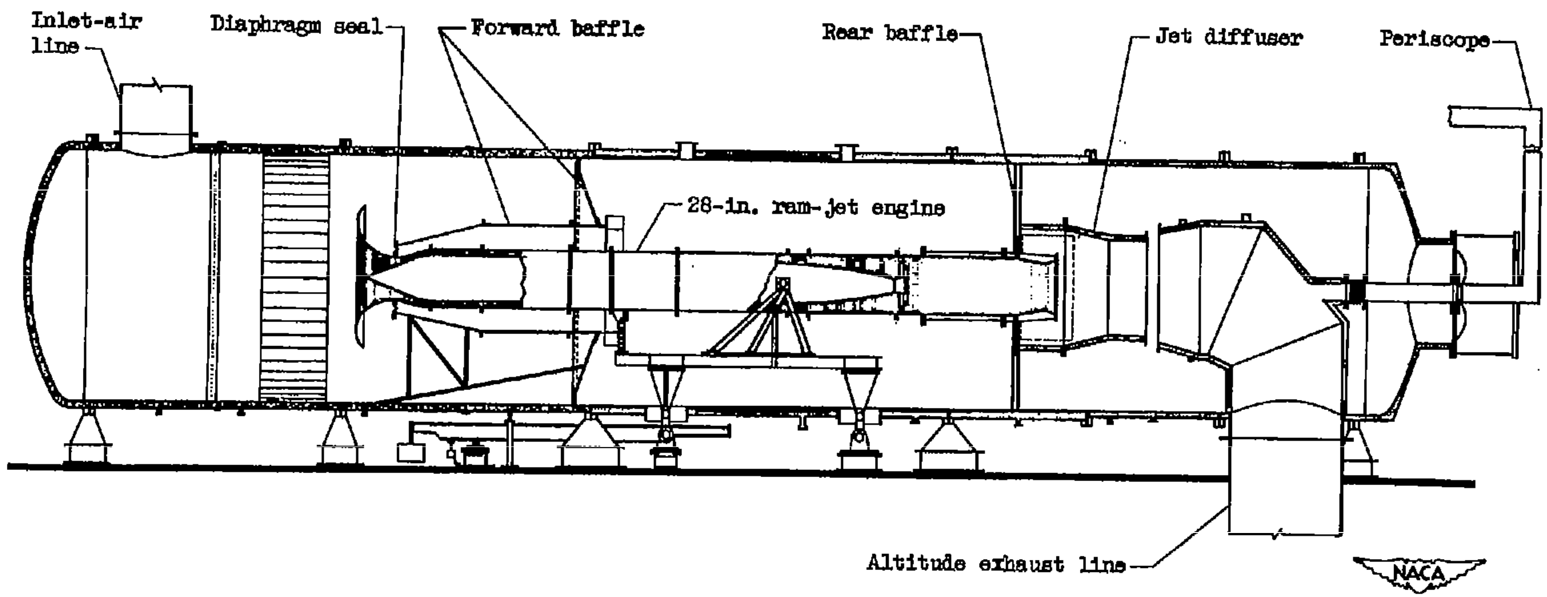

Figure 2. - Schematic diagram of 28-inch ram-jet engine installed in 10-foot altitude test chamber.

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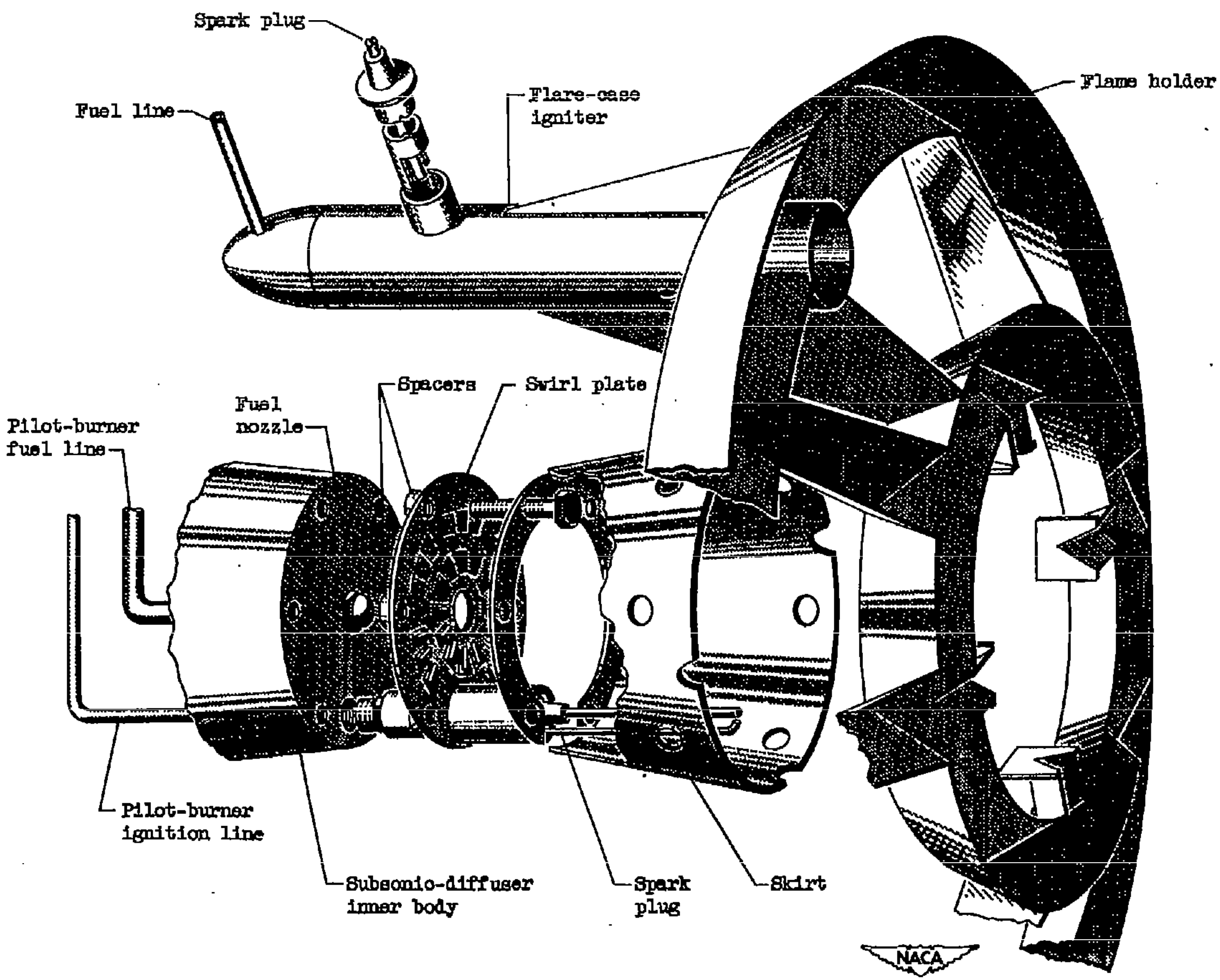

Figure 3. - Exploded view of pilot-burner and flame-holder assembly.

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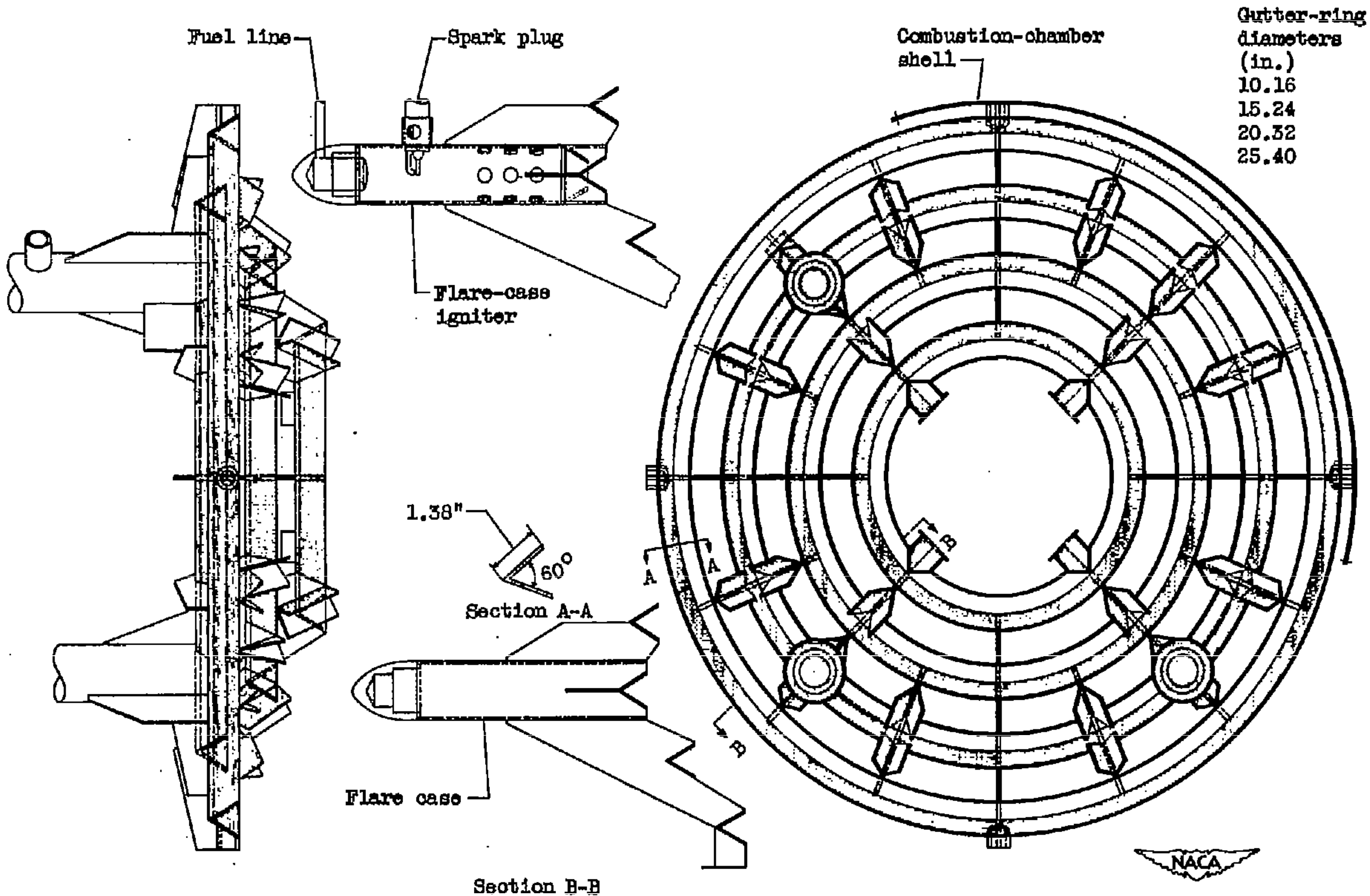

Figure 4. - Flame holder used for pilot-burner configuration 1. Gutter width, 1.38 inches; blocked area, 54.0 percent.

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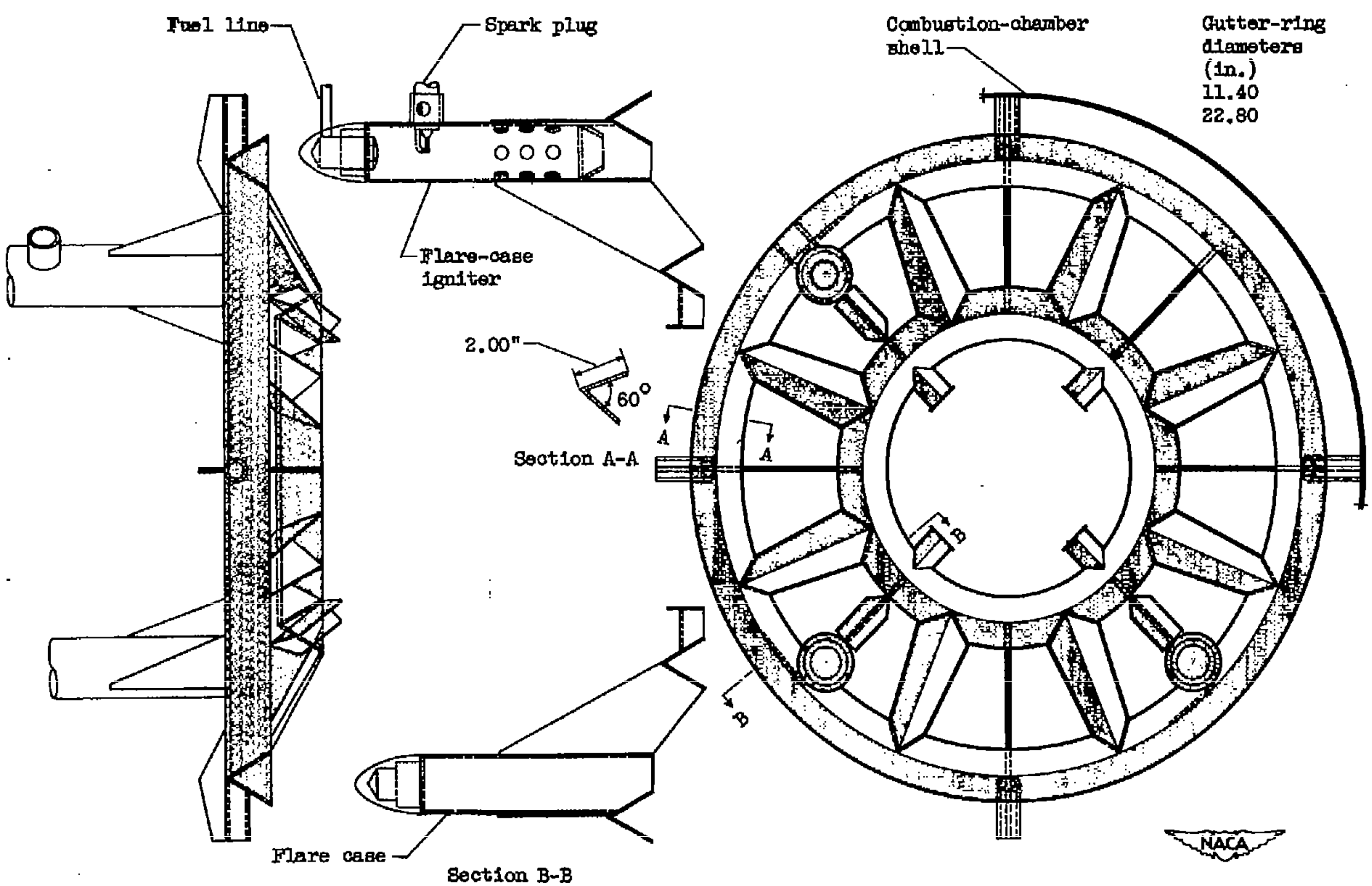


Figure 5. - Flame holder used for pilot-burner configuration 2. Gutter width, 2.00 inches; blocked area, 45.0 percent.

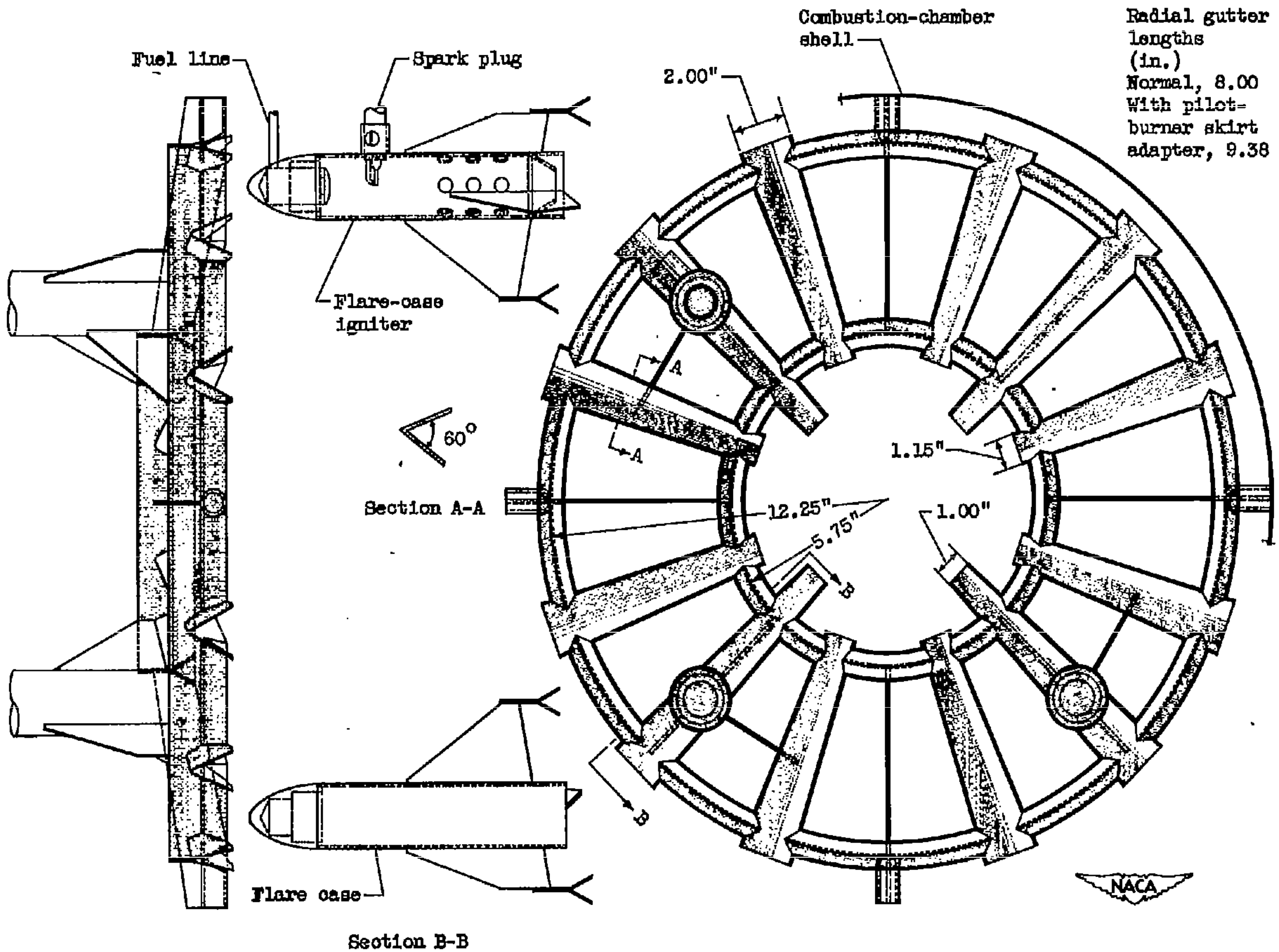
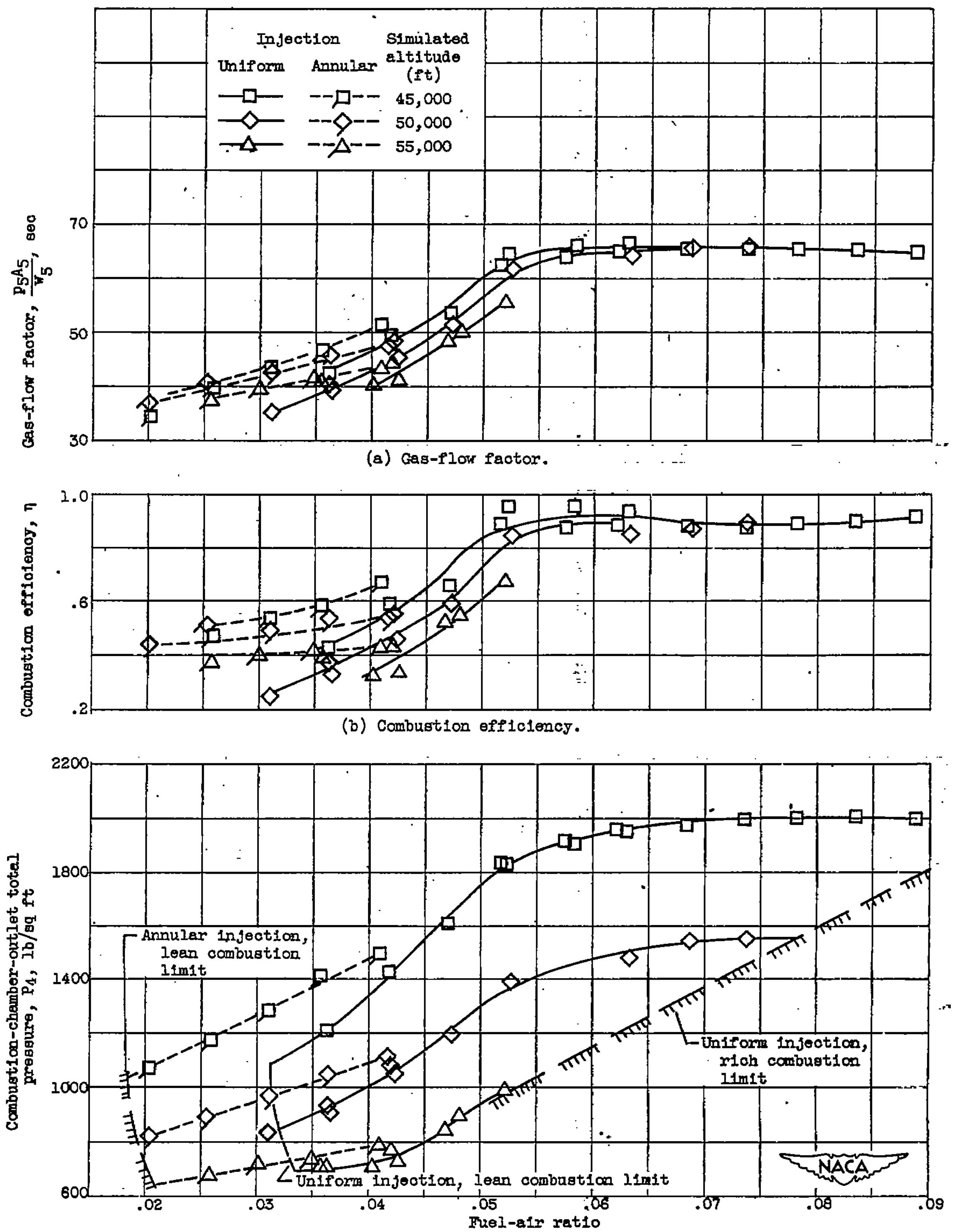


Figure 6. - Flame holder used for pilot-burner configuration 3. Radial gutters; blocked area, 41.0 percent.

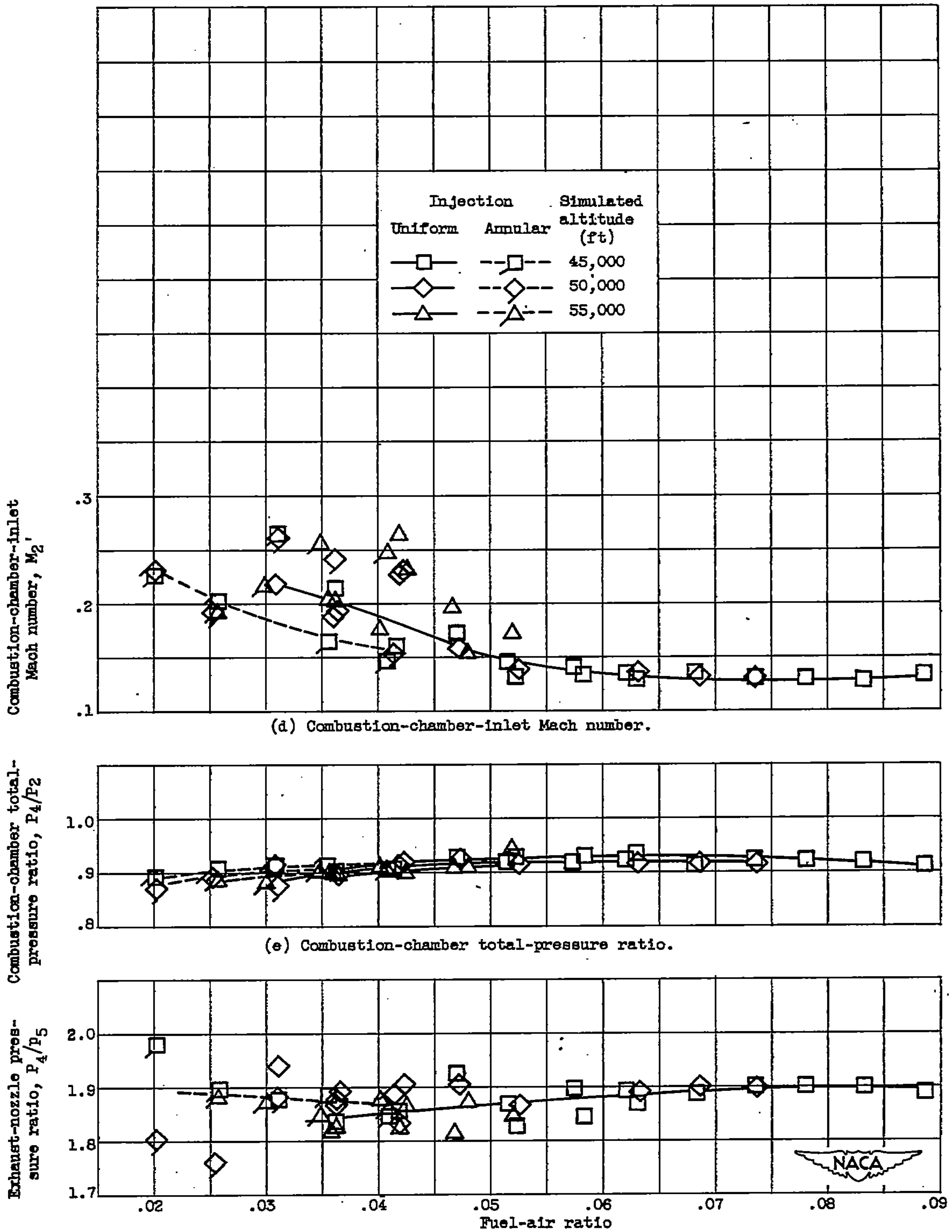


(c) Combustion-chamber-outlet total pressure and limits of combustion.

Figure 7. - Combustion-chamber performance variables for pilot-burner configuration 1. Flame holder: four-ring, 1.38-inch annular gutters; 54.0-percent blocked area.

2025

2025



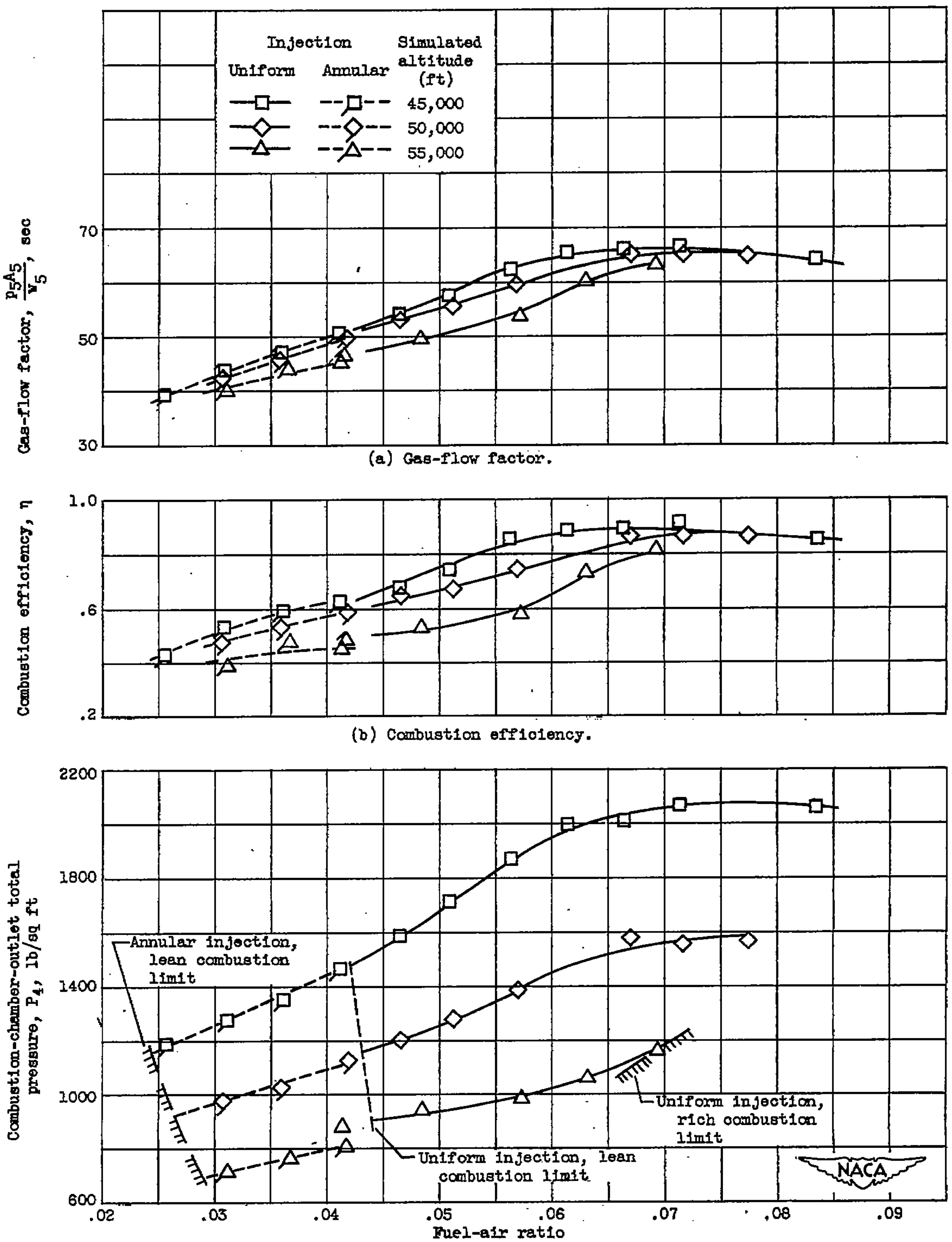
(d) Combustion-chamber-inlet Mach number.

(e) Combustion-chamber total-pressure ratio.

(f) Exhaust-nozzle pressure ratio.

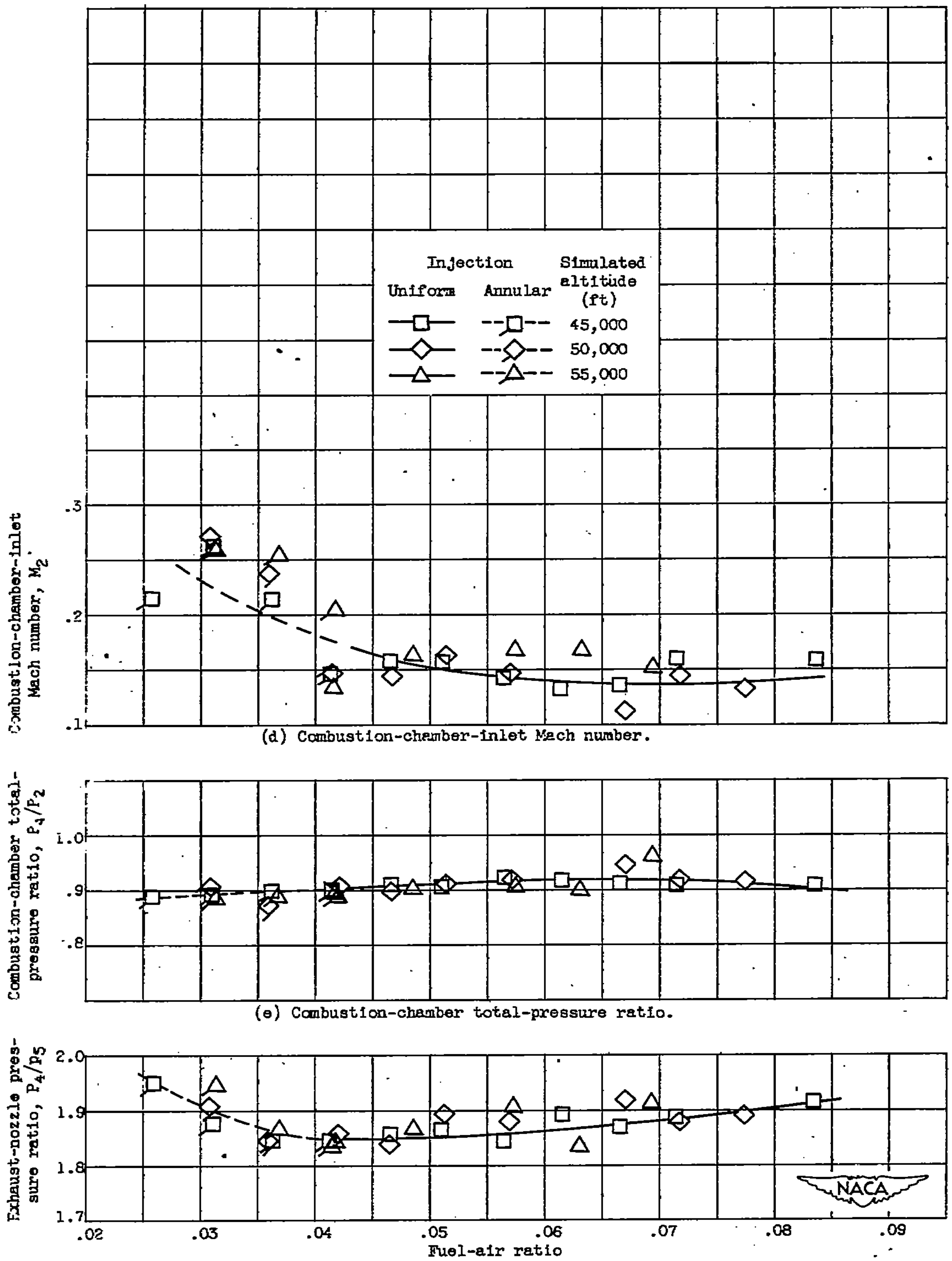
Figure 7. - Concluded. Combustion-chamber performance variables for pilot-burner configuration 1. Flame holder: four-ring, 1.38-inch annular gutters; 54.0-percent blocked area.

2025



(c) Combustion-chamber-outlet total pressure and limits of combustion.

Figure 8. - Combustion-chamber performance variables for pilot-burner configuration 2. Flame holder: two-ring, 2.00-inch annular gutters; 45.0-percent blocked area.

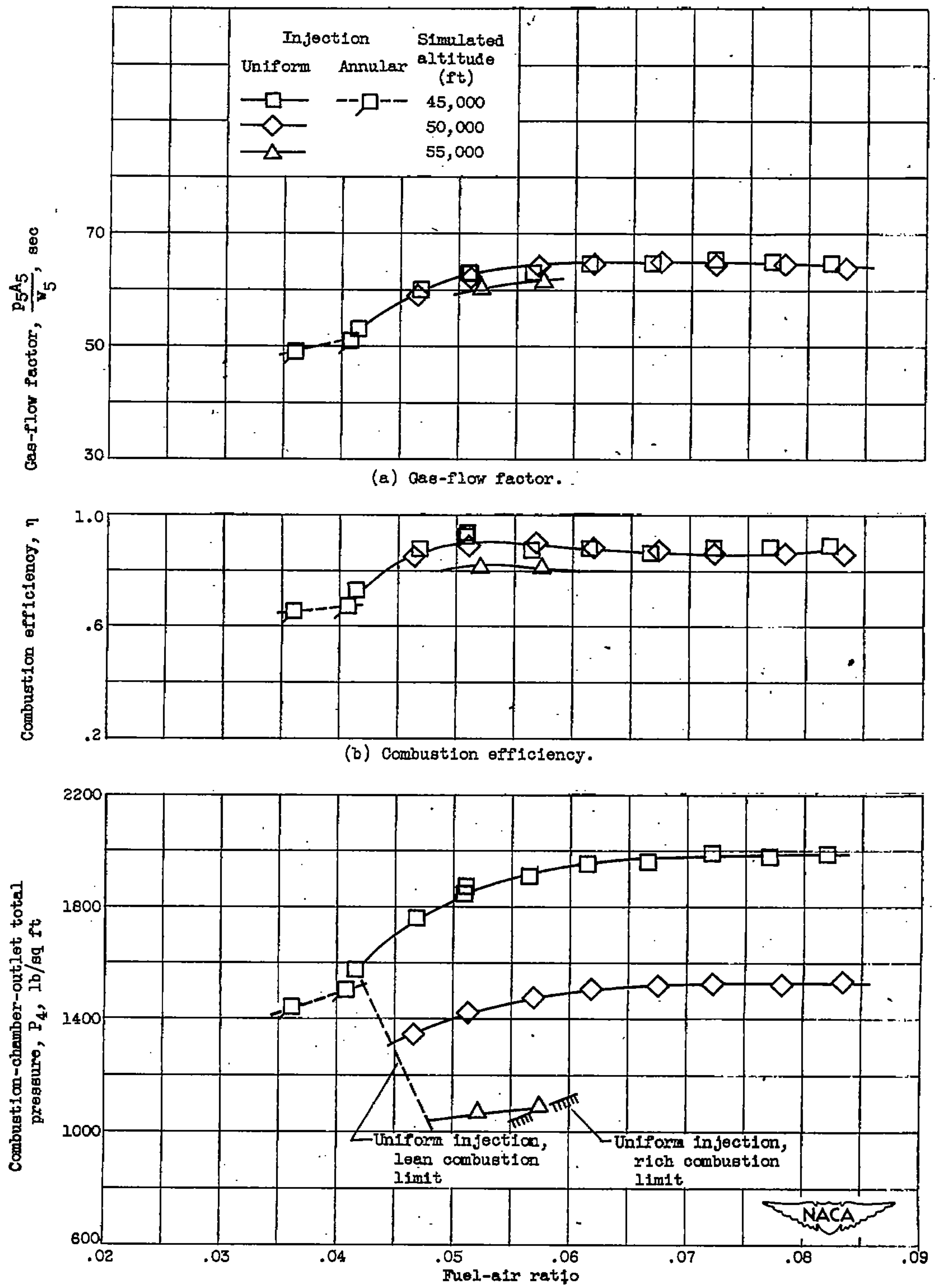


(d) Combustion-chamber-inlet Mach number.

(e) Combustion-chamber total-pressure ratio.

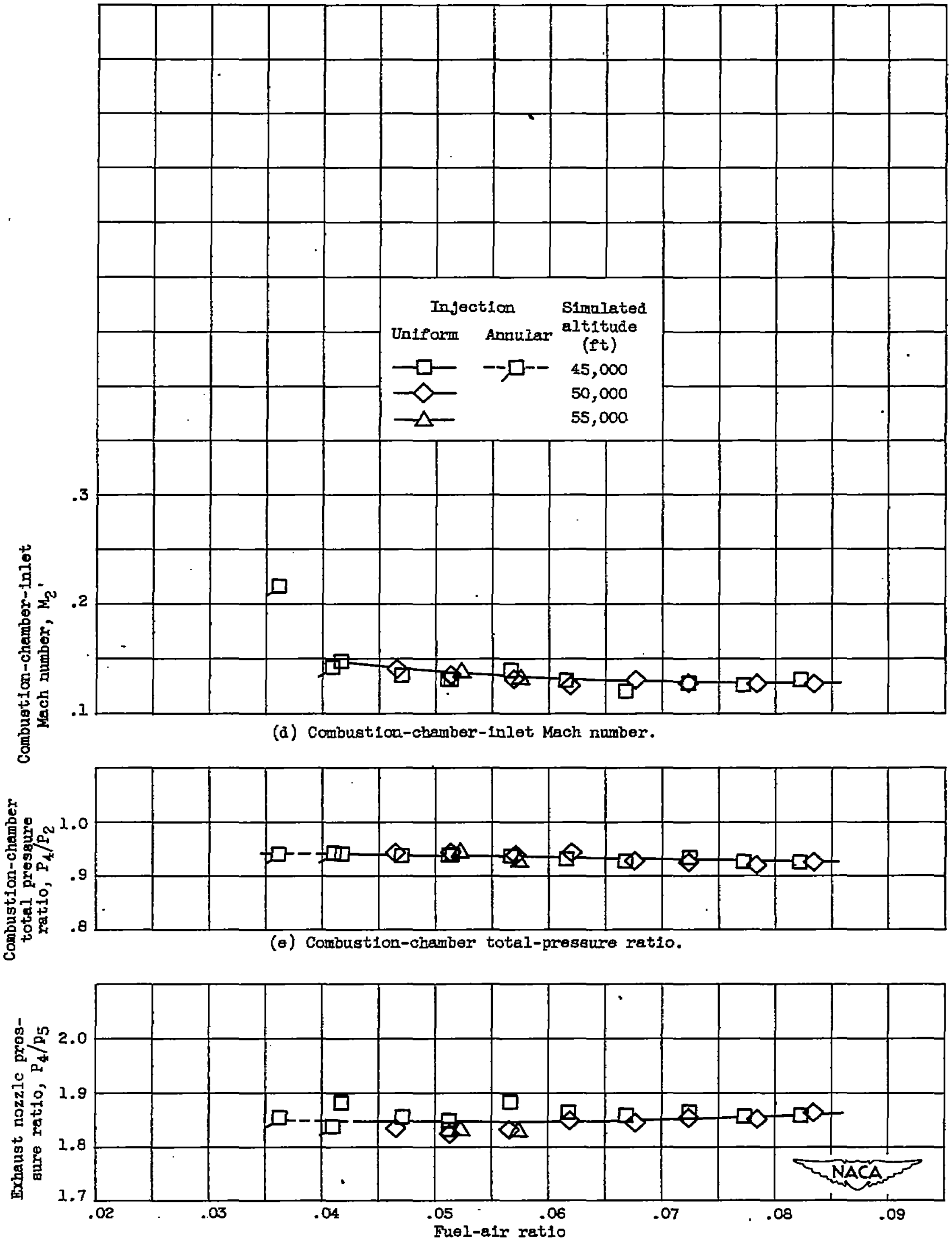
(f) Exhaust-nozzle pressure ratio.

Figure 8. - Concluded. Combustion-chamber performance variables for pilot-burner configuration 2. Flame holder: two-ring, 2.00-inch annular gutters; 45.0-percent blocked area.



(c) Combustion-chamber-outlet total pressure and limits of combustion.

Figure 9. - Combustion-chamber performance variables for pilot-burner configuration 3. Flame holder: radial gutters; 41.0-percent blocked area.



(d) Combustion-chamber-inlet Mach number.

(e) Combustion-chamber total-pressure ratio.

(f) Exhaust-nozzle pressure ratio.

Figure 9. - Concluded. Combustion-chamber performance variables for pilot-burner configuration 3. Flame holder: radial gutters; 41.0-percent blocked area.

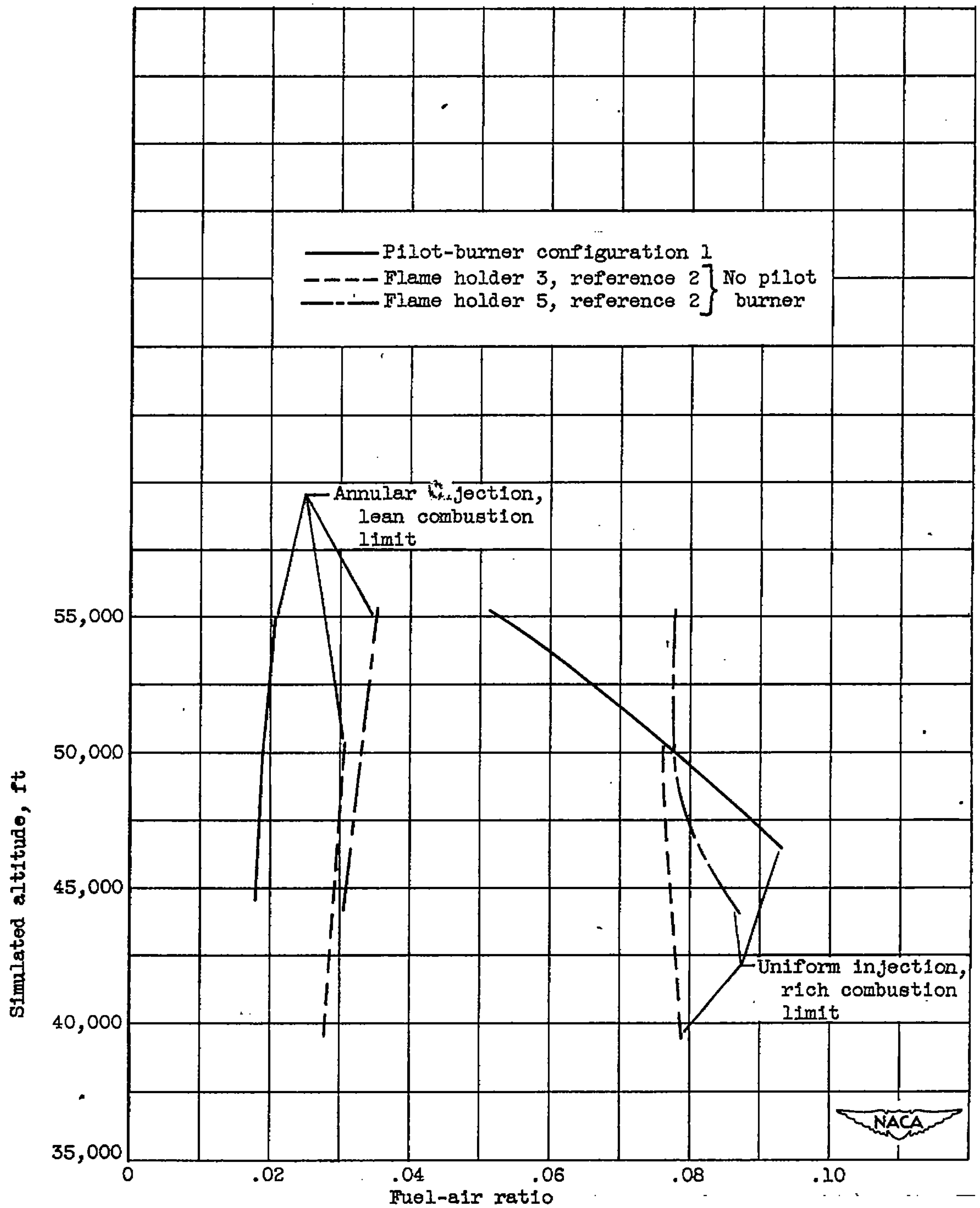
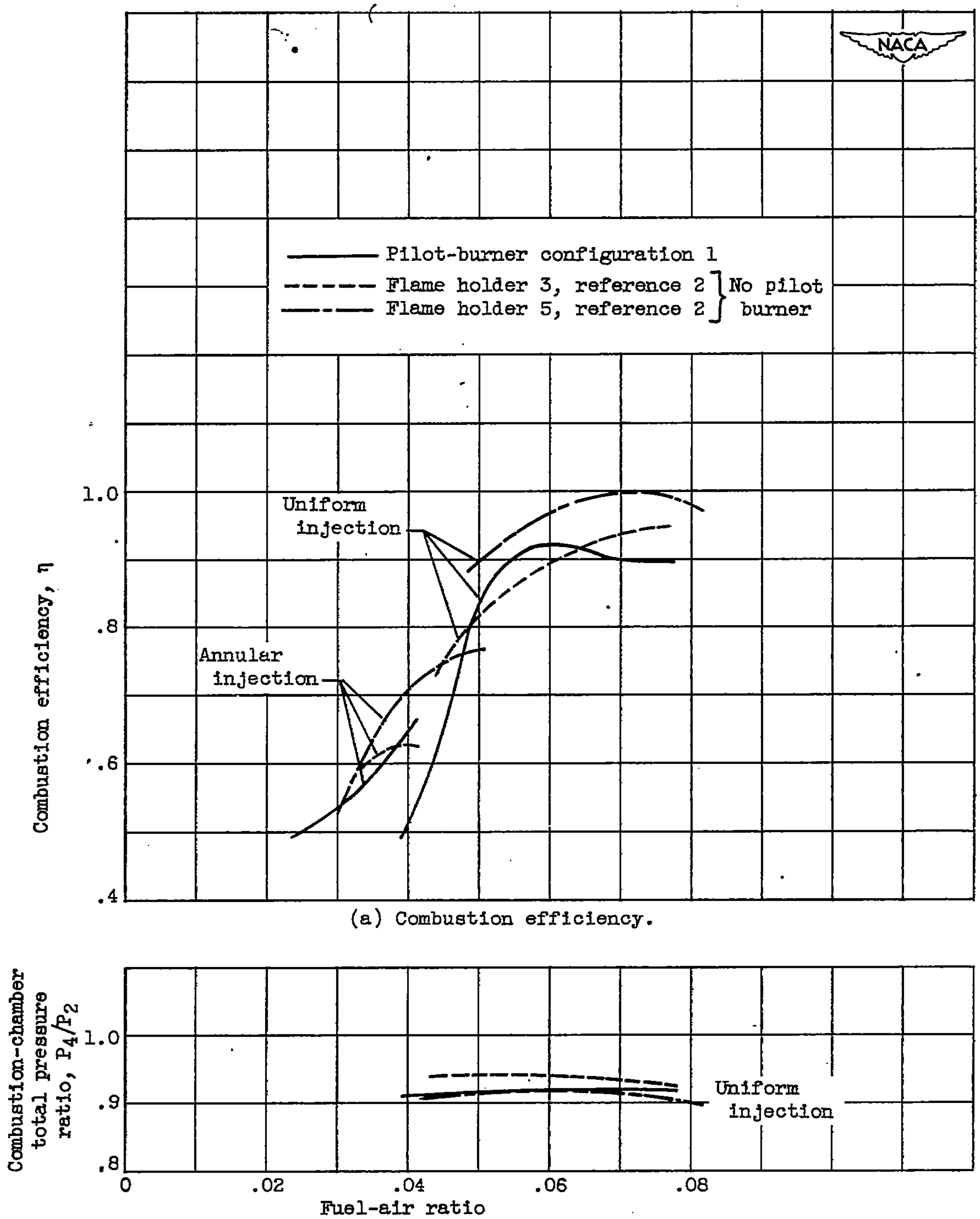


Figure 10. - Comparison of limits of combustion for configurations with and without pilot burner.



(a) Combustion efficiency.

(b) Combustion-chamber total-pressure ratio.

Figure 11. - Comparison of combustion efficiency and combustion-chamber total-pressure ratio for configurations with and without pilot burner. Simulated altitude, 45,000 feet.

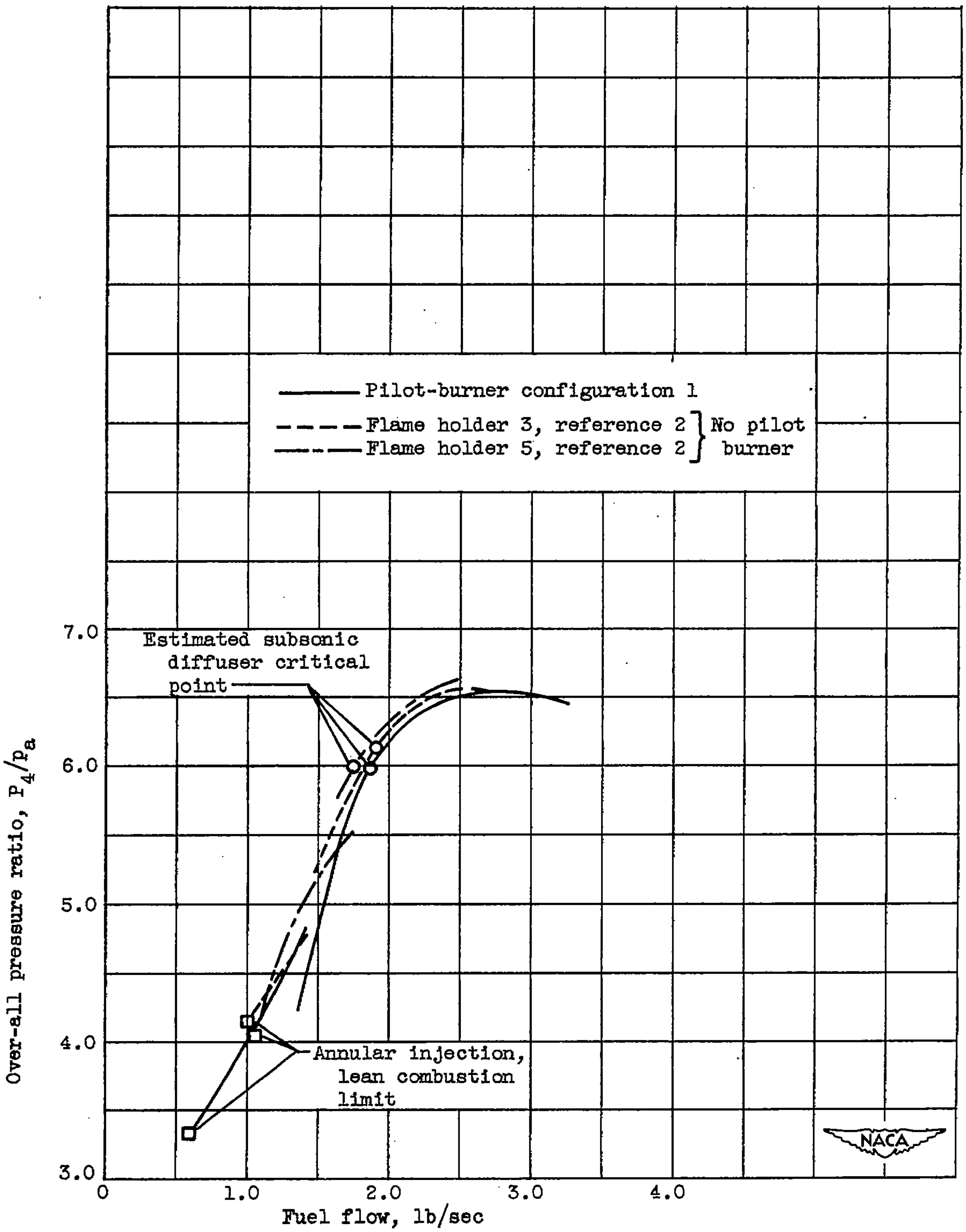


Figure 12. - Comparison of over-all pressure ratio for configurations with and without pilot burner. Simulated altitude, 45,000 feet.

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